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EFFECTS OF RECENT NASA-ARC HYPERVELOCITY IMPACT RESULTS ON METEOROID FLUX AND PUNCTURE MODELS

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ABSTRACT

Recent NASA-ARC laboratory hypervelocity impact results are used to derive a formula for the just-puncturable thickness of a metallic target sheet. The derived formula is used for an interpretative comparison of photographic meteor data and the puncture data from the three Pegasus and two Explorer meteoroid measurement satellites. The logarithm of the mass-cumulative influx of meteoroids per square meter per second is found to be a nonlinear function of the logarithm of the least-particle mass in grams. A cubic polynomial for this function, with -14.52, -1.406, -0.0490, and -0.00074 for the values of the coefficients of respective ascending powers, fits the data and seems most appropriate for extrapolation over the mass range for cometary particles. The influx of asteroidal particles is estimated separately.

*Ames Research Center.

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AERO-ASTRODYNAMICS LABORATORY

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LIST OF SYMBOLS

Symbol	Definition
$\emptyset$	puncture flux; mean number per second per square meter of surface with 2π steradian exposure
p	thickness of a just-puncturable sheet in centimeters
d	projectile or meteoroid diameter in centimeters
$F_>$	flux of meteoroids of mass equal to or greater than m; mean number of hits per square meter per second per 2π steradians without earth shielding
p_o	thick-target crater depth in centimeters
v	closing velocity in kilometers per second
C_t	longitudinal sonic velocity in infinite target of given material in kilometers per second
ϵ_t	target ductility, relative elongation in 2-inch gauge length
ρ_t	target specific gravity or density, gm/cm^3
ρ	projectile specific gravity or density, gm/cm^3
m	projectile or meteoroid mass in grams
log	logarithm to base ten
x_2	angle of impact of an incident particle from the surface normal
$\sigma_{\log m}$	standard deviation of log m
x	angle of impact of a puncturing particle from the surface normal
m_x	puncturable mass at constant angle of impact x_2
E[log m]	expected value or mean of log m
$\bar{v}$, $\bar{m}_x$	antilog of E[log v] and E[log m_x], respectively

LIST OF SYMBOLS (Continued)

Symbol	Definition
$k_t + \log p$	target parameter
k_t	target material parameter
$k_p + (19/54) \log m$	projectile parameter
k_p	projectile velocity parameter
D	distance from the sun in astronomical units

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SUMMARY

Recent NASA-ARC laboratory hypervelocity impact results are used to derive a formula for the just-puncturable thickness of a metallic target sheet. The derived formula is used for an interpretative comparison of photographic meteor data and the puncture data from the three Pegasus and two Explorer meteoroid measurement satellites. The logarithm of the mass-cumulative influx of meteoroids per square meter per second is found to be a nonlinear function of the logarithm of the least-particle mass in grams. A cubic polynomial for this function, with -14.52, -1.406, -0.0490, and -0.00074 for the values of the coefficients of respective ascending powers, fits the data and seems most appropriate for extrapolation over the mass range for cometary particles. The influx of asteroidal particles is estimated separately.

I. INTRODUCTION

A working paper [1] prepared for consideration by the NASA Meteoroid Technology Advisory Working Group* in January 1966 showed that the puncture data for the two Explorer and three Pegasus meteoroid measurement satellites collectively indicate that puncture flux ϕ is approximately proportional to the -1.966-power of the target equivalent thickness p. It was suggested that if the ratio of puncturable thickness, p, and particle diameter, d, can be considered proportional to the 1.04-power of d, then the mass-cumulative influx $F_{\geq}$ would be proportional to the -1.34-power of particle mass m for the puncturing particles similarly as for photographic meteors. That possibility is not very convincing; e.g., Gault [2] had concluded previously that the ratio of the thick-target crater depth, p_o, and the particle diameter, d, "should never be a strong function of the projectile size."

After further study and consultation, a report [3] was published with flux and puncture models for cislunar and interplanetary space. The cislunar part was distributed as a working paper [4] again to the NASA-MTAWG. The models presupposed: (1) The Ames (Summers 1959 [5]) formulation for thick-target penetration ratio p_o/d independent of d,

*Will be referred to as MTAWG in this report.

(2) the Langley (see Reference 6) relation between p_o and thin-target puncturable thickness, p, (3) Hawkins and Southworth's [7,8] sporadic photographic meteor sample with recalculated mass values [9] and Hawkins and Upton's [10] value for the flux of zero-visual-magnitude meteors and their "visibility" statistical weighting further supplemented [11, 12], (4) Stuhlinger's [13] thickest-target Pegasus puncture data, and (5) for the Explorer XVI thickest punctured target, Hastings [14] maximum likelihood value for the slope of the logarithm of the puncture flux, $\emptyset$, as a function of the logarithm of the target thickness, p. All of the reviewers expressed a preference for the models in Reference 4 instead of Reference 1.

II. RESPONSE FROM COORDINATION

Some of the suggestions which the reviewers* offered for a further improvement of the models in Reference 4 are as follows: (1) The photographic meteor tie point and slope should be determined from McCrosky and Posen's [15] sample which is nearly ten times as large as Hawkins' and Southworth's [7,8] 285-meteor sample. (2) The Pegasus puncture flux should be divided by 0.86 to account for the laboratory-determined counting efficiency reported by Naumann [16]. (3) The puncture data from Explorers XVI and XXIII should be considered collectively in the puncture flux model. (4) The more recent NASA-ARC hypervelocity impact data and analysis by Denardo and Nysmith [17] and by Fish and Summers [18] should be used instead of Summers' [5] earlier results. (5) The relation between thick-target penetration, p_o, and thin-target puncturable thickness, p, may depend on velocity (e.g., see Reference 19) so that p_o and p may scale with different powers of velocity especially for laboratory results with lower velocity than that for meteoroid impact.

III. EXCEPTION FOR PHOTOGRAPHIC METEORS

Although the results for the random sample of 285 sporadic photographic meteors published by Hawkins and Southworth [7,8] are said to have been determined by a more accurate method of data reduction than that which was used for the larger by McCrosky and Posen [15], the latter sample is almost ten times as large. Therefore, for purposes of statistical analysis, Öpik (see Dalton [20]) has stated a preference for the larger sample. The present analysis is based on the smaller sample in References 7 and 8 because results were available in Reference 12 for an appropriately weighted statistical analysis with respect to particle mass with mass values re-computed in Reference 9 with Öpik's [21, 1958] velocity dependence of meteor luminous efficiency. The mass values tabulated for the larger sample by McCrosky and Posen [15] are said to

*NASA-MTAWG members and their representatives.

follow the practice of the Harvard Meteor Project in assuming Öpik's [22,23] older formulation for luminous efficienty. The author's recent paper [11], attached as Appendix I to this report, shows how various statistical results are biased independently of any constant of proportionality for luminous efficiency. Therefore, in both the present and previous models [3], the ordinate and slope of log mass-cumulative influx $F_>$ (particles per square meter per second) as a function of log cometary particle mass m are -13.58 and -1.34, respectively, at $m = 10^{-0.68}$ grams. Velocity is nominally 26.7 km/sec.

IV. CRATER DEPTH AND PUNCTURABLE THICKNESS

Denardo and Nysmith [17] give a tabulation and plot of data for impact of 2017-T4 aluminum spheres into thick targets of 2024-T4 aluminum. The plot shows that log $p_o/d^{19/18}$ varies quite smoothly as a function of log v with slope gradually diminishing to about 2/3 at the highest velocity data-point. A tangential extrapolation to higher velocity will be assumed through this data point, which was tabulated from $p_o/d = 1.840$, $d = 0.159$ cm (1/16 in), and $v = 4.361$ km/sec (22,960 ft/sec). Therefore, by extrapolation,

$$\log[(p_o/d)(1/d)^{1/18}] = -0.254 + (2/3) \log v \tag{1}$$

for the given projectile and target materials.

For application of equation (1) to other target materials of the same density and ductility, it would seem that velocity v should be replaced by v/C_t, as in Summers' [5] formulation, where C_t is the sonic velocity in the target material. Bouma and Burkitt [24] give $C_t = 6.25$ km/sec for 2024-T4. Then, by rewriting equation (1) with v replaced by $v/(C_t/6.25)$,

$$p_o/d = 10^{0.277}\, d^{1/18}\, (v/C_t)^{2/3}, \tag{2}$$

for targets of the given density and ductility and the given projectile density.

The formulation with respect to the thin-target puncturable thickness p is found from equation (2) by replacing p_o with p/1.59 as in [3]; i.e.,

$$p/d = 10^{0.478}\, d^{1/18}(v/C_t)^{2/3}, \tag{3}$$

for targets of the given density and ductility and the given projectile density.

Fish and Summers [18] show results for puncturable thicknesses of various targets impacted by 0.159-centimeter-diameter balls of 2017-T4 aluminum ranging from 0.5 to 8.5 km/sec. Stating that "although a threshold penetration equation is not available at this time, one can note several factors which affect the thickness penetrated" they showed a tendency for:

$$p/d \sim (1/\epsilon_t)^{1/18}(1/\rho_t)^{1/2}\, v, \tag{4}$$

where ϵ_t and ρ_t are, respectively, the ductility and specific gravity of the target. Equation (4) is for the given projectile with constant d, etc. The velocity term in equation (4) will be ignored because it will be assumed that v must be replaced by $v^{2/3}$ as in equation (3) when the velocity is extrapolated to values typical of meteoroid impact.

The values for ductility ϵ_t and density ρ_t presupposed in equation (3) are those for a 2024-T4 target; i.e., [18,24], $\epsilon_t = 0.19$ and $\rho_t = 2.77$. Then, by equation (4) the right side of equation (3) can be multiplied by $(0.19/\epsilon_t)^{1/18}$ for targets of different ductility. But the sonic velocity in equation (3) is $C_t \sim \rho_t^{-1/2}$ for materials [25] with the same Young's modulus and Poisson's ratio. Then the dependence on target density in equation (4) is achieved by multiplying the right side of equation (3) by $(2.77/\rho_t)^{5/6}$. Therefore, equation (3) can be replaced by

$$p/d = 10^{0.807}\, d^{1/18}(1/\epsilon_t)^{1/18}\,(1/\rho_t)^{5/6}\,(v/C_t)^{2/3} \tag{5}$$

for spherical projectiles of 2017-T4 aluminum with density [18] $\rho = 2.79$.

The diameter, d, and the density, ρ, of the spherical projectile are related by

$$d\rho^{1/3} = (6m/\pi)^{1/3}, \tag{6}$$

where m is the projectile mass in grams. For a particle of given mass the right side of equation (5) is proportional to the cube root of kinetic energy; and for a particle of given velocity, the right side of equation (6) is also proportional to the cube root of kinetic energy, and is equated to the product of d and $\rho^{1/3}$. Then, if the data supporting equation (5) had involved projectiles of different density, it should be expected that d in equation (5) should be replaced by $d(\rho/2.79)^{1/3}$; i.e.,

$$p/(d\rho^{1/3}) = 10^{0.650}(d\rho^{1/3})^{1/18}\ \epsilon_t^{-1/18}\ \rho_t^{-5/6}\ (v/C_t)^{2/3}, \tag{7}$$

for spherical projectiles.

By substituting from equation (6) and transposing in equation (7), the thickness p of any target sheet just-puncturable by any projectile of mass m and typically cosmic velocity is

$$p = 10^{0.749}\ m^{19/54}\ \epsilon_t^{-1/18}\ \rho_t^{-5/6}\ C_t^{-2/3}(v \cos x_2)^{2/3}, \tag{8}$$

where (as in Reference 5) the velocity v for normal incidence has been replaced by the normal component $v \cos x_2$ for oblique impact.

V. PUNCTURABILITY OF PHOTOGRAPHIC METEOR PARTICLES

By equation (8), photographic meteor particle with mass $m = 10^{-0.68}$ gram,nominal closing velocity v = 26.7 km/sec, and angle of impact $x_2 = \pi/4$ radians would just puncture a sheet of 2024-T3 aluminum of thickness $p = 10^{0.502} = 3.18$ centimeters.

VI. PUNCTURE FLUX ENHANCEMENT FACTOR

To establish the relation between meteoroid incident flux $F_>$ and puncture flux, $\emptyset$, it is necessary to consider the statistical distribution of the mass m sufficient to puncture a given structure. Such an analysis was given in Reference 26 but with a different formulation for puncturability. Only the revisions for that analysis necessitated by equation (8) will be indicated here. When $F_>$ is the incident flux of particles with mass $m \geq \bar{m}$, where $\bar{m}$ is the value of m satisfying equation (8) when the nominal values $\bar{v}$ and $\bar{x}_2$ are used for v and x_2, then puncture flux, $\emptyset$, is enhanced by a factor 10^{β_5}; i.e.,

$$\emptyset = 10^{\beta_5}\ F_>. \tag{9}$$

It was found in Reference 3 that the slope β_2 of log $F_>$ as a function of log m varies from about $\beta_2 = -1.34$ for photographic meteors to about half that value for the Pegasus puncture data. It should be sufficiently accurate to consider β_5 as a constant determined from a constant $\beta_2 = -1$ and statistical independence of mass m and velocity v.

By equation (8), and $\sigma_{\log v} = 0.18$ from Reference 26,

$$\log m = (54/19)[-0.749 + \log(p\epsilon_t^{1/18}\ \rho_t^{5/6}\ C_t^{2/3})] - (36/19) \log(v \cos x_2), \tag{10}$$

$$\sigma_{\log m_x} = 0.34,$$

where m_x is puncturable mass at constant angle of impact x_2. By the derivation in Reference 26 for $E[\log \cos x_2] = -(1/2) \log e$,

$$E[\log m_x] = E[\log m] - (18/19) \log e - (36/19) \log \cos x_2,$$

$$\bar{m}_x = (\bar{m})(e^{-18/19})\ (\cos x_2)^{-36/19}.$$

Then, by substituting into the formulation in Reference 26 for the differential puncture flux, $d\emptyset$, corresponding to the differential impact angle dx_2,

$$d\emptyset = 6.94\ F_>(\cos x)^{36/19} \sin 2x\ dx, \tag{11}$$

where the subscript has been dropped from x in shifting attention from the incident particles to those that puncture. Then, by integrating the right side of equation (11) over the interval $0 \leq x \leq \pi/2$,

$$\emptyset = 3.56\ F_> = 10^{0.55}\ F_>. \tag{12}$$

The probability density function f(x) of the angle of impact, x, for the population of meteoroids which puncture a target exposed to an isotropic flux is, by equations (11) and (12),

$$f(x) = (d\emptyset/dx)/\emptyset = 1.95(\cos x)^{1.89} \sin 2x. \tag{13}$$

Although the puncture flux enhancement factor in equation (12) is somewhat smaller than was found in Reference 26, being 3.56 instead of 5.05, the probability density function f(x) for the angle of impact of puncturing meteoroids in equation (13) is not appreciably different from that which was found in Reference 26. Therefore, the derivation in Reference 26 for the most probable radiant of a particle puncturing a vehicle of known attitude is not compromised by the new formulation for puncturability by equation (8).

VII. TARGET AND PROJECTILE PARAMETERS

The puncture data from meteoroid measurement satellites is for target sheets of different thickness and of different materials. The puncture flux must be determined as a function of a target parameter which depends not only on the thickness but also on the other significant parameters of the material. The logarithm of equation (8) can be transposed to equate target and projectile parameters by

$$k_t + \log p = k_p + (19/54) \log m, \tag{14}$$

where the material parameter k_t is

$$k_t = -1.360 + (1/18) \log \epsilon_t + (5/6) \log \rho_t + (2/3) \log C_t \tag{15}$$

and where the projectile velocity parameter k_p is

$$k_p = -0.611 + (2/3) \log(v \cos x_2). \tag{16}$$

The constant terms in equations (15) and (16) have been mutually adjusted so that the target parameter, $k_t + \log p$, vanishes at the puncture flux tie point for photographic meteors. When meteoroid mass and velocity are assumed to be statistically independent and either the flux is isotropic or the target orientation is random, then nominally, by equation (16), equation (14) becomes

$$k_t + \log p = 0.240 + (19/54) \log m. \tag{17}$$

VIII. METEOROID PUNCTURE MODEL FOR EARTH ORBIT

In the cubic polynomial hazard model from Reference 3,

$$\log \emptyset = a_o + a_1(k_t + \log p) + a_2(k_t + \log p)^2 + a_3(k_t + \log p)^3, \tag{18}$$

it is necessary to re-evaluate the constants $a_o, \ldots, a_3$. Because the target parameter, $k_t + \log p$, vanishes nominally for photographic meteors with incident flux, $F_> = 10^{-13.58}$, and because the puncture flux enhancement factor in equation (12) is $10^{0.55}$, the value of a_o in equation (18) is

$$a_o = -13.58 + 0.55 = -13.03. \tag{19}$$

Also a_1 in equation (18) is the value of $d(\log \emptyset)/d(k_t + \log p)$ where $k_t + \log p$ vanishes. But for that condition, one also has from the photographic meteors $d(\log F)/d(\log m) = -1.34$. Then, by equations (12) and (17),

$$a_1 = -1.34(54/19) = -3.81. \tag{20}$$

The remaining two constants a_2 and a_3 in equation (18) can be determined from the data in Reference 3 by satisfying the centroid of the puncture data for the thickest target on each of the three Pegasus satellites and the centroid of all of the puncture data for the four relatively thinner punctured targets on Explorers XVI and XXIII. Then, when the puncture flux is divided by 0.86 to account for the counting

efficiency reported by Naumann [16], the tie point for the Pegasus targets is, for the first 99 punctures,

$$(\log \emptyset,\ k_t + \log p)_P = (-7.106,\ -1.883). \tag{21}$$

Also, the tie point for the Explorer targets is, with the first 104 punctures,

$$(\log \emptyset,\ k_t + \log p)_E = (-5.355,\ -2.633). \tag{22}$$

The values of the coefficients a_2 and a_3 which satisfy equations (18) through (22) are

$$a_2 = -0.384 \tag{23}$$

$$a_3 = -0.017. \tag{24}$$

Therefore, by equations (18) through (20), (23) and (24), the hazard model, with values compiled in Table 1 and illustrated in Figure 1, is

$$\log \emptyset = -13.03 - 3.81(k_t + \log p) - 0.384(k_t + \log p)^2 - 0.017(k_t + \log p)^3. \tag{25}$$

The results for a 2024-T3 target sheet are also given in Table 1 and Figure 3.

IX. MASS-CUMULATIVE INFLUX

By equations (12), (19), and (25), the mass cumulative influx $F_>$ can be calculated from

$$\log F_> = -13.58 - 3.81[0.240 + (19/54) \log m] - $$
$$- 0.384[0.240 + (19/54) \log m]^2 - 0.017[0.240 + (19/54) \log m]^3 \tag{26}$$

$$\log F_{>} = -14.52 - 1.406(\log m) - 0.0490(\log m)^2 - 0.00074(\log m)^3. \quad (27)$$

This result is illustrated in Figure 2 for the values compined in Table 1.

TABLE 1

Earth-Orbit Hazard-Model Values

$k_t + \log p$	$\log p$ 2024-T3 al	$\log m$	Cometary Particles		Asteroidal Particles	
			$\log \emptyset$	$\log F_{>}$	$\log \emptyset$	$\log F_{>}$
- 4.60	-4.098	-13.76	- 1.97	- 2.52	- 1.63	- 2.17
- 4.40	-3.898	-13.19	- 2.25	- 2.80	- 2.19	- 2.74
- 4.20	-3.698	-12.61	- 2.54	- 3.09	- 2.76	- 3.32
- 4.00	-3.498	-12.05	- 2.85	- 3.40	- 3.33	- 3.88
- 3.80	-3.298	-11.48	- 3.16	- 3.71	- 3.90	- 4.45
- 3.60	-3.098	-10.91	- 3.50	- 4.05	- 4.47	- 5.02
- 3.20	-2.698	- 9.78	- 4.21	- 4.76	- 5.61	- 6.15
- 2.80	-2.298	- 8.64	- 5.00	- 5.55	- 6.74	- 7.29
- 2.40	-1.898	- 7.50	- 5.86	- 6.41	- 7.88	- 8.43
- 2.00	-1.498	- 6.37	- 6.81	- 7.36	- 9.02	- 9.56
- 1.60	-1.098	- 5.23	- 7.85	- 8.40	-10.15	-10.70
- 1.20	- 0.698	- 4.09	- 8.98	- 9.53	-11.29	-11.84
- 0.80	- 0.298	- 2.96	-10.22	-10.77	-12.43	-12.97
- 0.40	0.102	- 1.82	-11.57	-12.12	-13.56	-14.11
0.00	0.502	- 0.68	-13.03	-13.58	-14.70	-15.25
0.40	0.902	0.46	-14.62	-15.17	-15.84	-16.39
0.80	1.302	1.59	-16.33	-16.88	-16.97	-17.52
1.20	1.702	2.73	-18.18	-18.73	-18.11	-18.66

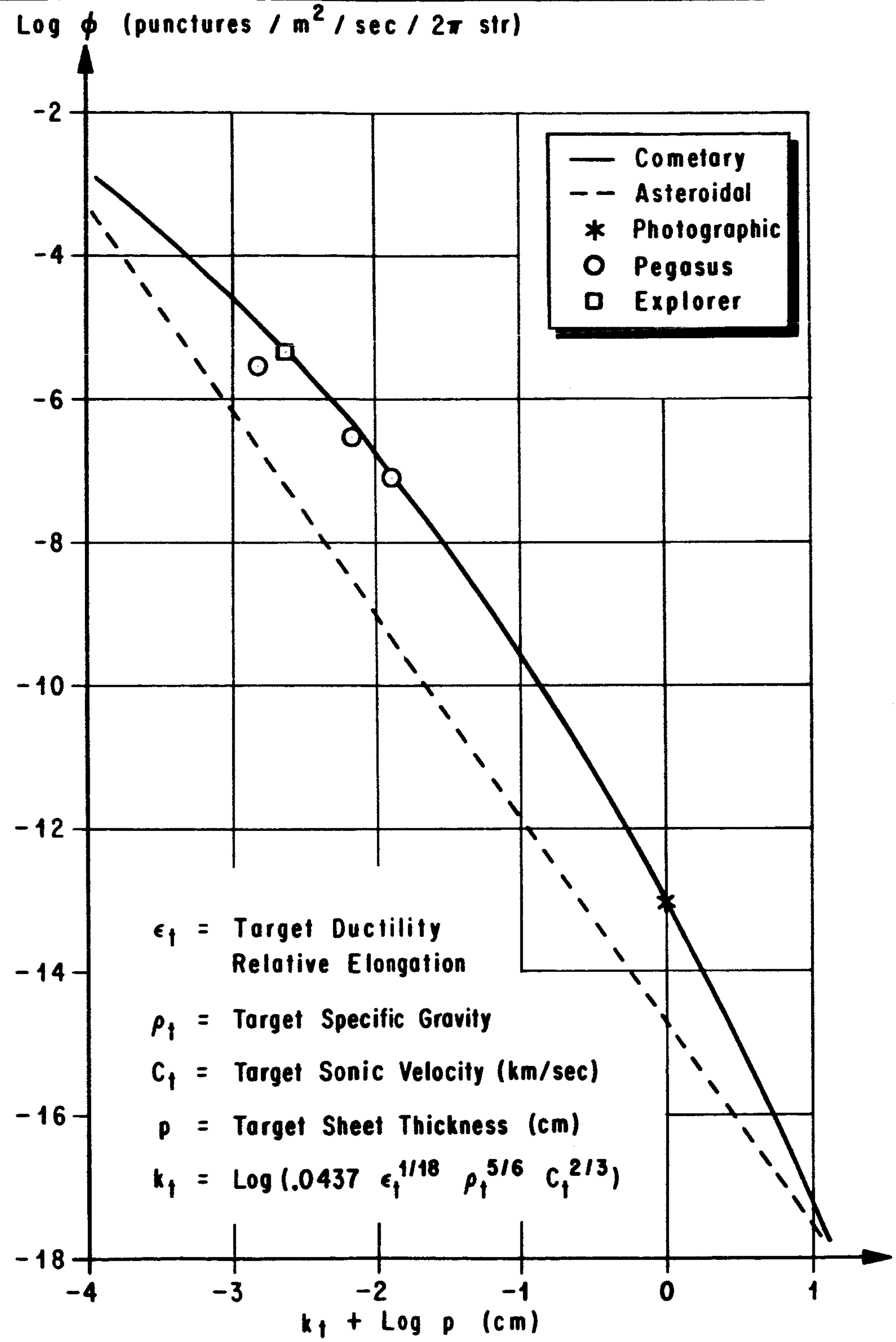

FIG. 1. MEAN CISLUNAR METEOROID PUNCTURE FLUX

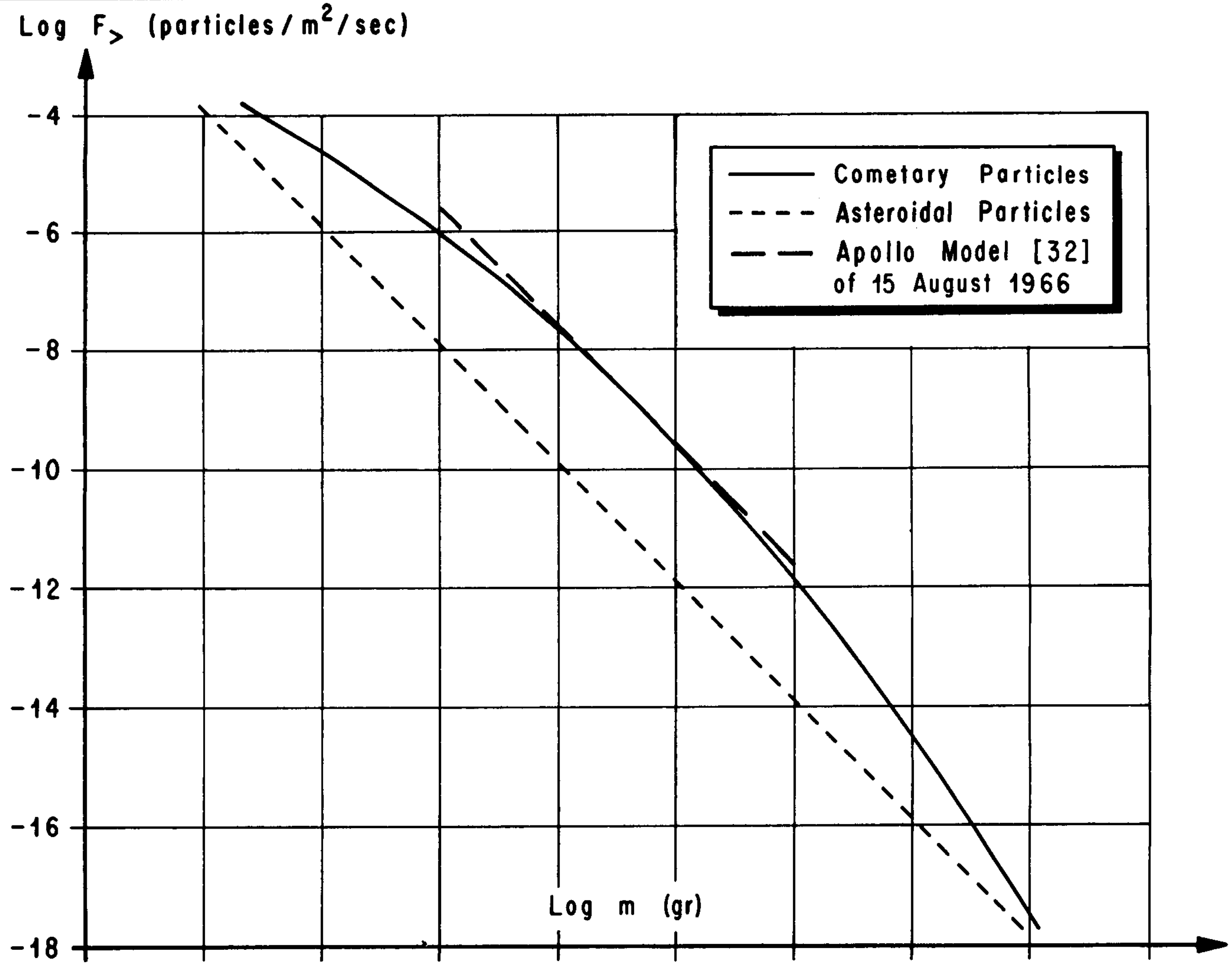

FIG. 2. METEOROID MASS-CUMULATIVE MEAN INFLUX

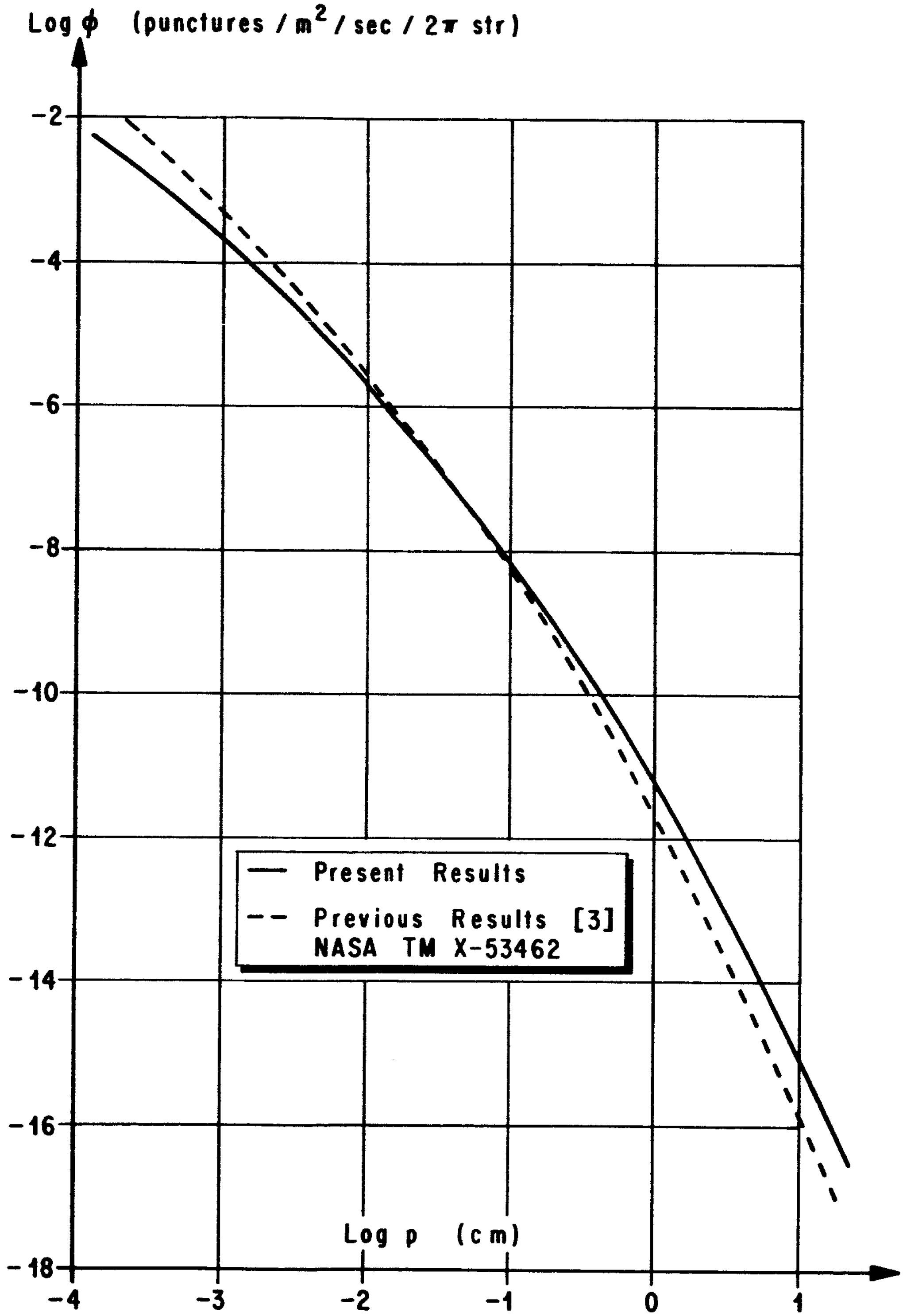

FIG. 3. MEAN CISLUNAR COMETARY METEOROID PUNCTURE FLUX FOR 2024-T3 ALUMINUM

X. ASTEROIDAL PARTICLES

As in Reference 3, the mass-cumulative influx of asteroidal particles is considered to be $10^{-15.93}\ m^{-1}$ particles per square meter per second for puncture-hazard purposes. This influx, with values compiled in Table 1 and illustrated also in Figure 2 is an extrapolation of Hawkins' [27] model for large stones. Then, by assuming the same velocity distribution as for photographic meteors, it follows by equations (12) and (17) that the asteroidal puncture flux, $\emptyset$, in earth-orbit can be calculated from

$$\log \emptyset = -14.70 - (54/19)(k_t + \log p). \tag{28}$$

Values for this result are also compiled in Table 1 and illustrated in Figure 1.

XI. CISLUNAR SPACE

The analysis of the meteoroid velocity distribution in Reference 3 showed that the effect of the earth's gravitational field is much less than had been expected. Consequently, only 25 percent of the terrestrial influx of cometary particles was found to be due to the gravity-effect factor; i.e., the gravitational enhancement factor is 4/3. According to Parkinson [28], the corresponding factor for asteroidal particles is 2.1.

XII. INTERPLANETARY SPACE

Most of the puncture hazard in cislunar space, and in interplanetary space near or between the orbits of Earth and Mercury, is due to particles of cometary origin. This follows from Figure 1, from McCoy's [29] preference for Beard's [30] estimate that the flux of cometary particles should be proportional to $D^{-3/2}$ (where D is the distance from the sun in astronomical units), and from Parkinson's [28] model for the distribution of asteroidal particles with respect to mass, m, and distance, D; i.e.,

$$F_{>} \sim D^{-3/2}. \tag{29}$$

The 27 kilometers per second median lunar impact velocity, for the distribution developed in Reference 3, is only slightly less than the heliocentric circular orbital velocity for the particular heliocentric distance. Anyway, it would seem appropriate to assume that, at any other heliocentric distance, D, nominal closing velocity is proportional to $D^{-1/2}$; i.e.,

$$v = 27D^{-1/2}, \tag{30}$$

for both cometary and asteroidal particles. Then, by equation (8), the thickness of a target nominally puncturable by a meteoroid of particular mass is

$$p \sim D^{-1/3}. \tag{31}$$

Also, by equation (8), $p^{54/19} \sim mv^{36/19}$; i.e., together with the result in equation (30), it follows that the particle mass $\bar{m}$ nominally sufficient to puncture a particular target is

$$\bar{m} \sim D^{18/19}. \tag{32}$$

Therefore, cometary puncture flux, $\emptyset$, is changed not only by the factor $D^{-3/2}$ due to the change in the mass-cumulative flux $F_>$ but also by the factor

$$D^{(18/19)\ \partial(\log F_>)/\partial(\log m)} \simeq D^{-18/19}.$$

These two factors combine to give

$$\emptyset \sim D^{-93/38}. \tag{33}$$

These results for cometary particles, equations (29) and (33), are thought to be applicable between the orbits of Mercury and Jupiter, except that for close orbits around Jupiter it is necessary to account for the significant effects of the gravitational field of the planet. But only for $D \leqq 1$ is it safe to ignore the asteroidal particles.

Because of the relative sparsity of the asteroidal meteoroids in the terrestrial influx, pertinent information about this population is less substantial. Parkinson [28] preferred the following flux enhancement factors for asteroidal particles with respect to heliocentric distance: 1.0, 2000, 30000, and 20 for the orbits of Earth, Mars, asteroids (at 2.5 A.U. point of max.), and Jupiter, respectively. The Jovian and terrestrial gravitationally enhanced flux factors for asteroidal particles were also given by Parkinson [28] as 170 and 2.1, respectively.

XIII. ACCURACY

In Reference 3 it was stated that the models which were developed for the influx $F_{>}$ and the corresponding puncture flux $\emptyset$ were thought to be accurate to within a factor 2 probable error (normal distribution), or to within a factor 9 of the 3-σ level of 99.86 percent one-sided confidence. The estimate of the accuracy was intended only as a quantitative expression of engineering judgment. Contrarily, the author has been told both that there is no scientific basis for (or value of) any quantitative distribution of intensity-of-belief and that the model for puncture flux is accurate to within a factor less than 2 even at the 3-σ level for half-mil (0.00127-centimeter) 2024-T3 aluminum foil. Calculation for this target by the model in Reference 3 gives $\emptyset = 2.87 \times 10^{-4}$, but equation (25) in the present analysis gives $\emptyset = 1.41 \times 10^{-4}$, and the 29 June 1966 model by Naumann [31] gives $\emptyset = 7.72 \times 10^{-6}$. Differences in these results are due to alternative extrapolations from essentially the same data.

The author has been advised* that the puncture flux $\emptyset$ in equation (21), for the Pegasus tie point based on the first 99 punctures in the thickest target, should be considered accurate to within a factor $(99 + 99^{1/2})/99 = 1.10$ at the 1-σ level or 84 percent one-sided confidence. But that would involve only a conditional probability which would presuppose the suitability of a set of assumptions. For example, it would be assumed that the target had a uniform thickness over the entire area and of known value. The actual thickness of the aluminum sheet used in the capacitor puncture transducer was given by Naumann [16] as 406 ± 50 microns, later said to be from the specifications. Testing procedures ordinarily presuppose both a consumer's risk and a producer's risk; i.e., there is a chance that both a substandard item is accepted and that a good item is rejected. Anyway, a 50-micron increment in thickness would correspond to an increment of 0.049 in the value of the target parameter, $k_t + \log p$, in equation (21). And, by differentiation of equation (25), this would correspond to a 33 percent reduction in the puncture flux.

*MSFC participants deliberating on a meteoroid model for Project Able, August 1966.

The present analysis is thought to be more accurate than the one in Reference 3; but it seems prudent to retain the estimate that the influx $F_>$ by equation (26) and the corresponding puncture flux $\emptyset$ by equation (25) are accurate to within a factor 2 probable error.

XIV. CONCLUSIONS

When the laboratory hypervelocity impact results reported by Summers [5], by Denardo and Nysmith [17], and by Fish and Summers [18] are interpreted collectively with some restrictions for extrapolation to cosmic impact velocity, a relation can be anticipated between the projectile mass, m, in grams and the thickness, p, in centimeters of a just-puncturable metallic target. The present state-of-the-art favors equating projectile and target parameters by

$$k_t + \log p = k_p + (19/54) \log m, \tag{14}$$

where the material parameter k_t is

$$k_t = -1.360 + \log(\epsilon_t^{1/18} \rho_t^{5/6} C_t^{2/3}) \tag{15}$$

and where the projectile velocity parameter k_p is

$$k_p = -0.611 + \log(v \cos x_2)^{2/3}. \tag{16}$$

The other parameters in equations (15) and (16) are, for the target, ductility (relative elongation) ϵ_t, specific gravity ρ_t, and sonic velocity C_t (km/sec), and for the projectile, velocity v (km/sec) and angle of impact x_2 from the normal.

The statistical distributions of velocity v and angle of impact x_2 are such that a target sheet with a 2π-steradian exposure to the meteoroid influx will have a puncture flux, $\emptyset$, exceeding the mass-cumulative influx, $F_>$, by a factor approximately 3.56; i.e., a particle with mass, m, and ordinary values of v and x_2 will just puncture the target, and $F_>$ presupposes m.

In earth-orbit the mean number of punctures, $\emptyset$, per square meter per second per 2π-steradian exposure for cometary meteoroids can be calculated from

$$\log \emptyset = -13.03 - 3.81(k_t + \log p) - 0.384(k_t + \log p)^2 - 0.017(k_t + \log p)^3. \tag{25}$$

The corresponding formula for asteroidal meteoroids is

$$\log \emptyset = -17.70 - (19/54)(k_t + \log p). \tag{28}$$

Corresponding to equation (25) the mass-cumulative influx $F_>$ of cometary meteoroids can be calculated from

$$\log F_> = -14.52 - 1.406(\log m) - 0.0490(\log m)^2 - 0.00074(\log m)^3; \tag{27}$$

and for asteroidal meteoroids, corresponding to equation (28),

$$\log F_> = -15.93 - \log m. \tag{34}$$

These results for cometary meteoroids, given numerically in Table 1 and illustrated in Figures 1 through 3, are thought to be accurate to within a factor 2 probable error, or a factor 9 at the 3σ level.

In interplanetary space the puncture flux, $\emptyset$, and mass cumulative flux, $F_>$, for cometary particles are related to solar distance D by

$$F_> \sim D^{-3/2} \tag{29}$$

$$\emptyset \sim D^{-93/38}; \tag{33}$$

but only for $D \leqq 1$ A.U. is it safe to ignore the asteroidal particles.

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APPENDIX I

Reference 11. AIAA Paper No. 66-515

Velocity Dependence of Meteor Luminous Efficiency and Consequent Statistical Results. CHARLES C. DALTON, Scientific Assistant, Aerospace Environment Division, Aero-Astrodynamics Laboratory, NASA-Marshall Space Flight Center, Huntsville, Ala.

ABSTRACT

A systems analysis basis of decision between Öpik's and Verniani's velocity dependence of meteor luminous efficiency is given. A weighting function is used to transform Hawkins and Southworth's random sample of 285 sporadic photographic meteors into a random sample of meteoroids incident upon a randomly placed and randomly oriented surface at air-entry altitude. Each of the sample sets of mass values for the two luminous efficiency formulations is ranked with respect to material mass and partitioned at a mass value which gives subsets of comparable statistical weight. The extent to which the subsets of a set give different distributions of a parameter such as velocity tends to be more generally convincing than the numerical value of the linear correlation between that parameter and mass. The results favor Öpik's theory and give some basis, when a sufficiently large sample is used, for showing the directional dependence of the cumulative flux with respect to a function of mass and velocity.

Photographic meteor data are pertinent in the construction of models for meteoroid protection of personnel, equipment, vehicles, and stations in space because the measurable parameters have been accurately determined for statistically significant samples. But in applying these data to meteoroid hazard considerations, two major difficulties are encountered, with the result that the analysis is less nearly direct than one might have expected.

The main difficulty with meteor data in the analysis of puncturability is that, e.g., by extrapolation of Summers' [1] hypervelocity impact data to a typical meteor velocity, crater depth is a function of the density and kinetic energy of the particle. Thus, the luminous efficiency for the conversion of particle kinetic energy into meteor luminous intensity must be invoked. But the meteoroids not only are of uncertain chemical composition and physical characteristics, but also have typical closing velocity higher than that currently available in laboratory experiments. Then the luminous efficiency must be inferred from the physical theory of meteors.

Another difficulty with meteor data in the analysis of hazards in space is that, due to physical selectivity, a random sample of meteor data is produced by particles which do not constitute a random sample of the particle influx. Consequently, it is necessary to calculate what relative statistical weight the different members of the sample must be given so that selectivity will not bias the statistical distribution of the parameters of interest.

The sample used, both in the present study and in one previously reported by the author [2,3] with different weighting, is Hawkins and Southworth's [4,5] random sample of 285 sporadic meteors doubly photographed by the Baker Super-Schmidt cameras to a limiting photographic magnitude of +4 from stations at Doña Ana and Soledad, New Mexico, from February 1952 to July 1954.

The main purpose in both analyses is to study the effect on the statistical relationships between five particle parameters - log mass, log velocity, arithmetic celestial latitude, heliocentric orbital eccentricity, and radiant deviation from the earth-way apex - when Öpik's [6] and Verniani's [7,8] formulations for luminous efficiency are interchanged. The mass values tabulated by Hawkins and Southworth [5] for this sample are said (by Verniani [9]) to be proportional to those which would follow from Verniani's [7,8] more recent formulation of luminous efficiency directly proportional to velocity. A scale translation was also made in the computation of mass values by Öpik's [6] theory; but the present results are sensitive only to the velocity-dependence.

In both the present and the previously reported study [2,3], the weighting function has three factors. A factor inversely proportional to the square of the meteor height accounts for the variation in the effective surveillance area. The asymmetry in the distribution with respect to the ecliptic plane, due to the latitude of the station, was reduced by weighting inversely with the fraction of the radiant circle of celestial latitude apparent above the horizon and by doubling the weight of each element with radiant north celestial latitude numerically greater than the numerically greatest southern celestial latitude. The remaining factor in the weighting function was different in the two analyses; being inversely proportional to the 3/2-power of velocity in that previously reported [2,3], and directly proportional to Hawkins and Upton's [10] inverse relative visibility $g(\mu)$ in the present analysis, where μ is the meteor magnitude above the limit of the photographic plate; i.e.,

$$
\begin{aligned}
g &= 1 && \text{for } \mu > 1.85, \\
&= 10 && \text{for } \mu < 0.55, \\
&= (0.71\mu - 0.296)^{-1} && \text{for } 0.55 \leqq \mu \leqq 1.85.
\end{aligned}
$$

The previous analysis with mass values by Öpik's [6] theory (Dalton [2]) gave results about as one might have expected for the 285 meteor sample. The correlation between log mass and log velocity was only 0.01, the corresponding partial correlation was 0.10, and the multiple correlation for the five variables was only 0.21. But with the mass values by Verniani's [7,8] theory (Dalton [3]), the same correlations were -0.69, 0.41, and 0.72, respectively.

Meteor cosmic weight as a function of velocity v, as used by Whipple [11] for $v > 19$ km/sec, and as used for all values of v by McCrosky and Posen [12] and by Jacchia and Whipple [13], has a factor v^{-2} which contains the factor $v^{-1/2}$ because meteor height was assumed to vary as $v^{1/4}$. But McCrosky and Posen [12] estimated that the uncertainty in the velocity mass law and in the number-luminosity law are such that corrections for these effects will probably be in error by at least 1 in the velocity exponent.

There was, therefore, a reasonable suspicion that the seemingly anomalous correlations might represent bias due to inappropriate velocity weighting. But the results now to be shown for weighting as a function of meteor magnitude above the limit of the photographic plate do not support that expectation.

Figure 1 compares Öpik's [6] meteor luminous efficiency with a hypothetical luminous efficiency proportional to v^n, where the ordinate n is unity for Verniani's [7,8] theory. The unit negative value for n, which Öpik [6] suggested as an approximation, agrees very well as a typical value for his more detailed results, but is not assumed for the present analysis.

Figure 2 shows, for each of the sets of computed mass values for the same meteors, the weighted correlations between the five particle parameters: log mass, log velocity, radiant arithmetic celestial latitude, heliocentric orbital eccentricity, and radiant total elongation from the earth-way apex. The most striking differences are noted for the correlation r_{12} between the logarithms of mass and velocity (-0.83 vs -0.11), for the corresponding partial correlation $r_{12 \cdot 345}$ (0.35 vs 0.06), and for the multiple correlation $r_{1.2345}$ (0.84 vs 0.20). The widely different results for the correlation r_{14} between log mass and eccentricity (-0.55 vs 0.01) seem to be consequent to the high value 0.77 for the correlation r_{24} between log velocity and eccentricity. In the Verniani [7,8] theory, with luminous efficiency proportional to velocity, the higher velocity meteors have relatively higher luminous efficiency, and consequently they have a lower calculated value for particle mass.

Figure 3 shows that, when the sample is ordered with respect to the Öpik [6] mass values and partitioned into subsets of equal statistical weight, the distribution of eccentricity is not very different for the two subsets. This result reflects the value 0.01 for the correlation r_{14} between log mass and eccentricity with the Öpik [6] mass values.

Figure 4 shows the corresponding distributions of eccentricity in subsets of equal statistical weight formed by a partition of the sample ordered with respect to the Verniani [7,8] mass values. Although it would seem that these widely different distributions of eccentricity might be difficult to explain physically, they reflect the value 0.55 for the correlation r_{14} between log mass and eccentricity with the Verniani [7,8] mass values.

Figure 5 shows, for velocity, what the preceding figure showed for eccentricity. These results, which reflect the value -0.83 for the correlation r_{12} between the logarithms of mass and velocity with the Verniani [7,8] mass values, would seem to be even more difficult to explain physically.

Figure 6, however, showing the corresponding results with the Öpik [6] mass values, seems about what one should have expected for a sample of 285 meteors without any velocity weighting. These results reflect the value -0.11 for the correlation r_{12} between the logarithms of mass and velocity. Therefore, it seems appropriate to consider that both the statistical weighting and the Öpik velocity dependence of luminous efficiency are pertinent for a determination of the directional dependence of the cumulative flux with respect to a function of mass and velocity.

Figure 7 shows the distribution of radiants as a function of the total deviation from the earth-way apex. The ordinate, the ratio of the probability density and the sine of the angle of displacement, is the relative density of radiants averaged around a circle concentric with the earth-way apex. The accentuated maximum in the vicinity of 90 degrees elongation was not expected, but it seems to be substantially established.

Figure 8 shows the distribution of the ecliptic component of the elongation from the earth-way apex. The probability density functions for this paper, such as the one shown in this figure, were obtained by ordering the sample with respect to the parameter of interest and drawing a smooth curve through the vicinity of the machine-plotted point-by-point relative cumulative distribution. The values of the slope of that curve, determined at the parameter values of interest, are the values of the probability density function.

Figure 9 represents an attempt to show how, with a momentum-sensing impact-detection surface in earth orbit, one might infer the distribution of the ecliptic component of the radiant elongation from the earth-way apex. These results are found by deleting 30 percent of the meteors of lowest momentum. Figure 10 represents the corresponding results for a hypothetical detector with a particle energy threshold. Both results would seem to be inconclusive for a sample this small; but the technique might be useful with a larger sample. However, due to the value -0.88 of the correlation r_{25} between log velocity and elongation, the results would be spurious, if there remains any appreciable bias with respect to velocity in the weighting function.

Figure 11 shows the distribution of meteor radiants with respect to the ecliptic plane. The weighted determinations for the mean and median radiant deviation from the ecliptic plane are 26 and 18 degrees, respectively.

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FIG. 1. DEVIATION OF LOG ÖPIK'S LUMINOUS EFFICIENCY WITH RESPECT TO LOG VELOCITY

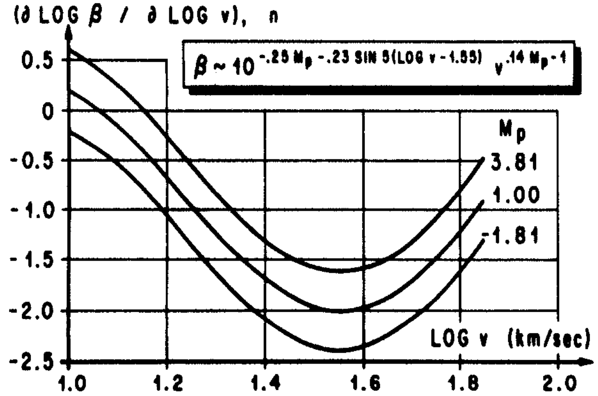


FIG. 2. CORRELATIONS BY WEIGHTED ANALYSIS

SUBSCRIPT	PARAMETER
1	LOG MASS
2	LOG VELOCITY
3	ARITHMETIC CELESTIAL LATITUDE
4	ECCENTRICITY
5	ELONGATION FROM EARTH-WAY APEX

CORRELATION	WITH VERNIANI MASS	WITH ÖPIK MASS
r_{12}	-0.83	-0.11
r_{13}	0.03	0.00
r_{14}	-0.55	0.01
r_{15}	0.78	0.16
r_{23}	-0.02	-0.02
r_{24}	0.77	0.77
r_{25}	-0.88	-0.86
r_{34}	-0.15	-0.15
r_{35}	0.06	0.06
r_{45}	-0.46	-0.46
$r_{1 \cdot 2345}$	0.84	0.20
$r_{12 \cdot 345}$	0.35	0.06
$r_{13 \cdot 245}$	0.07	0.03
$r_{14 \cdot 235}$	-0.16	-0.10
$r_{15 \cdot 234}$	0.00	0.01

FIG. 3. WEIGHTED DISTRIBUTION OF ECCENTRICITY FOR ÖPIK MASS REGIMES

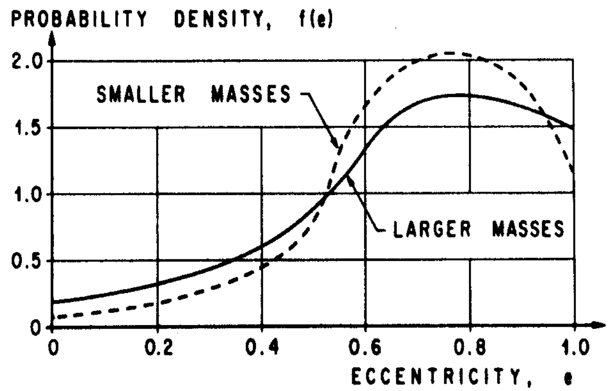


FIG. 4. WEIGHTED DISTRIBUTION OF ECCENTRICITY FOR VERNIANI MASS REGIMES

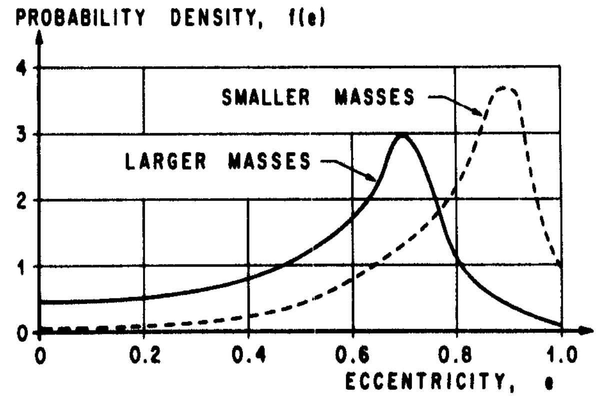


FIG. 5. WEIGHTED DISTRIBUTION OF VELOCITY FOR VERNIANI MASS REGIMES

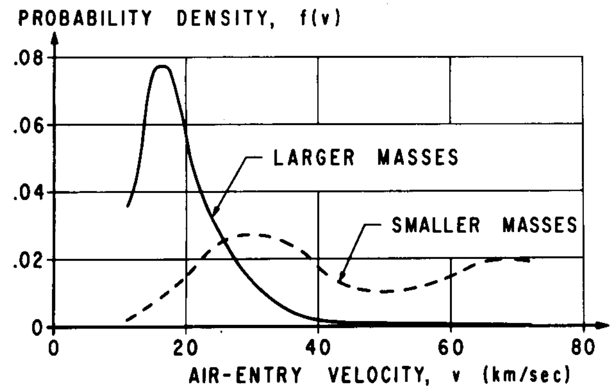


FIG. 6. WEIGHTED DISTRIBUTION OF VELOCITY FOR ÖPIK MASS REGIMES

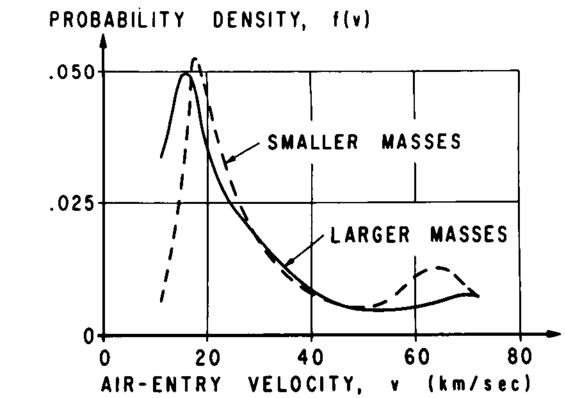


FIG. 7. WEIGHTED DENSITY OF RADIANTS VERSUS EARTH-WAY APEX DEVIATION

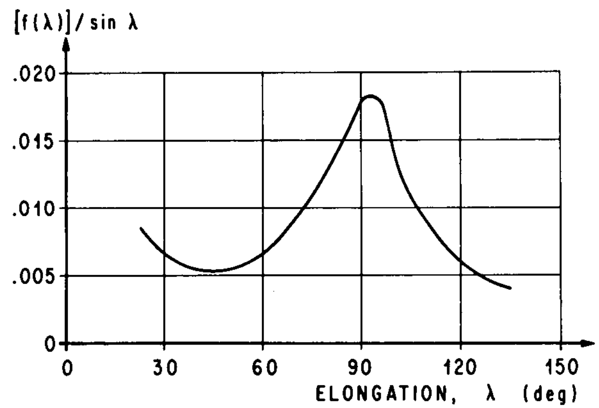


FIG. 8. WEIGHTED DISTRIBUTION WITH TOTAL SAMPLE

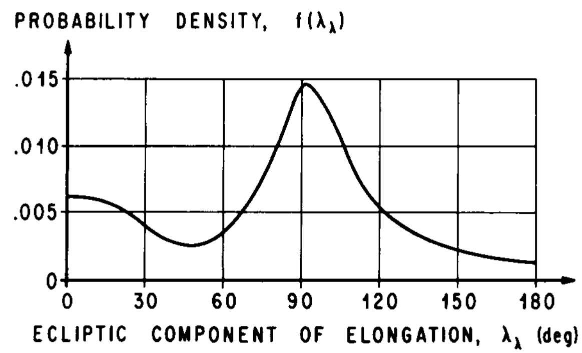


FIG. 9. WEIGHTED DISTRIBUTION WITH MOMENTUM THRESHOLD

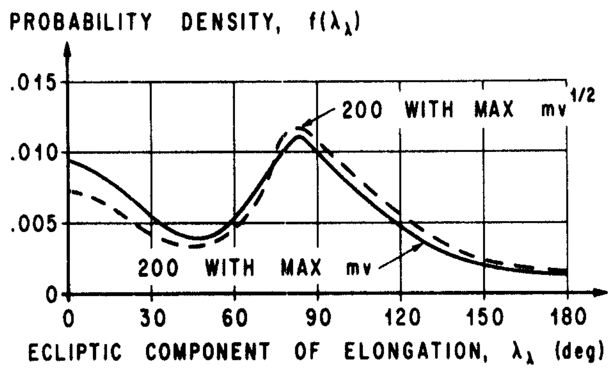


FIG. 10. WEIGHTED DISTRIBUTION WITH ENERGY THRESHOLD

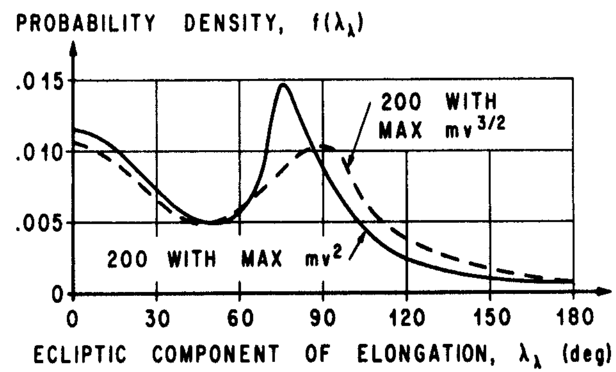
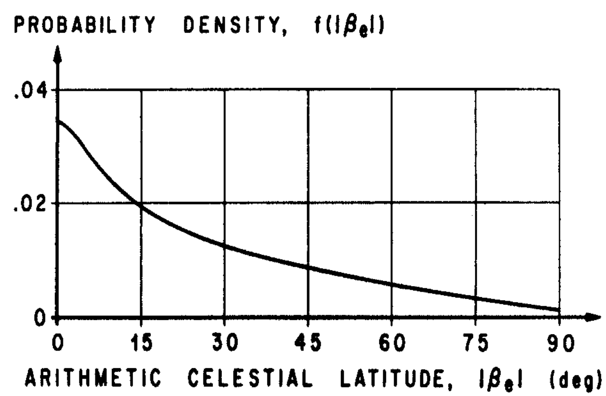


FIG. 11. WEIGHTED DISTRIBUTION OF CELESTIAL LATITUDE OF RADIANT



APPROVAL NASA TM X-53512

EFFECTS OF RECENT NASA-ARC HYPERVELOCITY IMPACT RESULTS ON METEOROID FLUX AND PUNCTURE MODELS

by Charles C. Dalton

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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